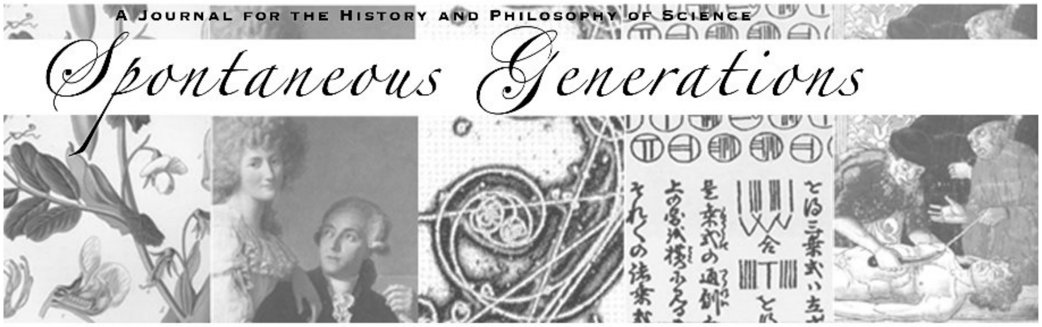

Reading Measuring Instruments

Author(s): Mario Bunge

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EDITORIAL OFFICES

Institute for the History and Philosophy of Science and Technology
Room 316 Victoria College, 91 Charles Street West
Toronto, Ontario, Canada M5S 1K7
hapsat.society@utoronto.ca

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Reading Measuring Instruments*

Mario Bunge†

The design, maintenance and use of all measuring instruments involve indicators of the thing, property, or event they are expected to detect or measure. And every quantitative indicator is a functional relation between imperceptible and perceptible facts–for example, the "flow" of time and the rotation of a watch's hands. The empirical test of any quantitative hypothesis involves the translation of the unobservable variables occurring in it into the observable variable(s) in the indicator hypothesis. Yet, indicators have escaped the notice of nearly all philosophers of science–a fact that may indicate unfamiliarity with laboratory work.

I. PHILOSOPHERS DISCOVER EXPERIMENT

Until recently almost all philosophers of science focused their work on theories, and overlooked instruments. Ian Hacking's *Representing and Intervening* (1983) was an instant hit among philosophers because it told them something that scientists had known since the Scientific Revolution: that experiment trumps observation and is no less important than conceptual representation.

True, half a century ago, what Patrick Suppes and his coworkers (e.g., Suppes and Zinnes 1959) called "measurement" theory attracted the

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† Mario Bunge was born in 1919 in Argentina, where he earned his PhD in physics, a discipline he taught in both his native country and in the United States. Between 1966 and 2009 he taught philosophy at McGill University. Dr. Bunge authored more than 500 papers and 50 books, among them *Causality* (1959), *Foundations of Physics* (1967), *Scientific Research*, 2 vols. (1967), *Treatise on Basic Philosophy*, in 8 vols. (1974-89), *The Mind-Body Problem* (1980), *Philosophy of Psychology*, with R. Ardila (1987), *Finding Philosophy in Social Science* (1996), *Foundations of Biophilosophy*, with M. Mahner (1997), *Chasing Reality* (2006), and *Political Philosophy* (2009). Springer is about to publish his *Matter and Mind*. He is a founding member of the Asociación Física Argentina and the founder of the Universidad Obrera Argentina, the philosophy journal *Minerva,* the Society of Exact Philosophy, and the Asociación Mexicana de Epistemología. He has been a visiting professor at a number of European and Latin American universities, and holds 19 honorary doctorates. Dr. Bunge is married to the mathematician Dr. Marta C. Bunge and has four children, all of them university professors. He was jailed twice and was denied national identity documents until after the fall of General Perón's government.

attention of many psychologists and philosophers. But it was soon shown (Bunge 1973) that the said theory had fatal flaws. Indeed, it involved the confusion of the mathematical concept of a measure (such as an area) with the empirical procedure of measurement; it dealt only with extensive (or additive) magnitudes such as length; and it did not involve the crucial concept of an indicator, or unobservable-observable bridge.

Not even van Fraassen's latest book (2008), where measurement has pride of place, mentions indicators: it presupposes that all measurements are direct, like those using measuring tapes. Worse, van Fraassen adopts the operationalist principle (Bridgman 1927) that the very construction of a magnitude involves reference to its measurement–as if it were possible to design a measuring instrument without having some idea of what it is expected to measure; and as if there were only one possible measurement procedure for each magnitude. And yet, as will be argued anon, there is no scientific measurement without indicators built into precision instruments, for only indicators allow one to read precision instruments.

By contrast, philosophers have largely ignored the earliest analytical writing on observation, measurement, and experiment (Bunge 1967a), perhaps because they involved the concept of an indicator, which is unfamiliar to philosophers. Another reason for that oversight may be that the said book showed that the standard view of the logic of theory testing is mistaken for the same reason: because it overlooks the need for translating the hypothesis to be tested into empirical or laboratory terms.

For example, the data relevant to electrodynamics do not contain the basic concepts of this theory, those of potential and current density, which are unmeasurable. Likewise, the energy operators and the state functions, basic to the quantum theory, are inaccessible to measurement. In general, the more basic a concept, the farther removed from the relevant data it is.

II. What Measuring Instruments Show

Measuring instruments are supposed to show, either on dials or on digital displays, the "tropes," or values of the desired properties. The scale, the ruler and the clepsydra were the earliest such tools: in fact, they were used by craftsmen and traders three millennia before they entered the laboratory. Of course, modern instruments are far more complex than their ancient precursors. But most measuring instruments, whether old or new, do not show directly the value of a property: what they show instead is the value of an *indicator*, that is, an observable counterpart of the unperceivable item. See the following table.

For instance, what one reads in a mercury thermometer is the level of the mercury column; and what one sees in a film exposed to the X-rays that went through a crystal are parallel bands or concentric rings.

Factual Item	**Indicator**
Atmospheric pressure	Height of barometric column
Wind speed	Angle of anemometer pointer
Electric current intensity	Angle of compass needle
Passage of charged particle	Geiger click
Crystal structure	X-ray diffraction pattern
Recession of galaxies	Galactic redshift
Acidity	pH
Health	Vital signs
Economic activity	GDP
Income inequality	Gini index
Quality of life	UN human development index
Probability	Relative frequency
Device	Microelectronics
Controlled droplet production	Fluid physics
Automatic pumps	Biotechnology

Table 1. Some examples.

In the former case the temperature is assumed to be proportional to the height of the mercury column. [More precisely, one uses the hypothesis "$h = h_0(1 + \alpha t + \beta t^2)$"]. In crystallography one interprets the figures appearing on film as diffraction patterns, and infers the crystal structure (an inverse problem) by solving a bunch of direct problems of this kind: one conjectures some plausible crystal configurations, uses Fourier analysis to calculate the resulting diffraction patterns, and compares them with the one seen in the film. This is of course how the founders of molecular biology tested their conjectures about DNA structure. (More on inverse problems, another subject overlooked by most philosophers, in Bunge 2006.)

III. Visualizing the Unseen

Much the same holds for experimental particle physics. For example, one cannot see proton trajectories: what one does see are the tracks left by protons and other charged particles in cloud chambers or photographic plates. And to "read" these tracks one uses the theory of ionization, that teaches that the dots in the visible trajectory (droplets or exposed emulsion grains) are the more dense, the lower the particle energy–which allows one to find out the direction of motion.

Particle physicists make also frequent use of the law of momentum conservation, which holds in quantum physics as well as in classical physics. This law is particularly handy in interpreting trajectories that seem to originate from nothing or to disappear into nothingness, as in the following diagrams:

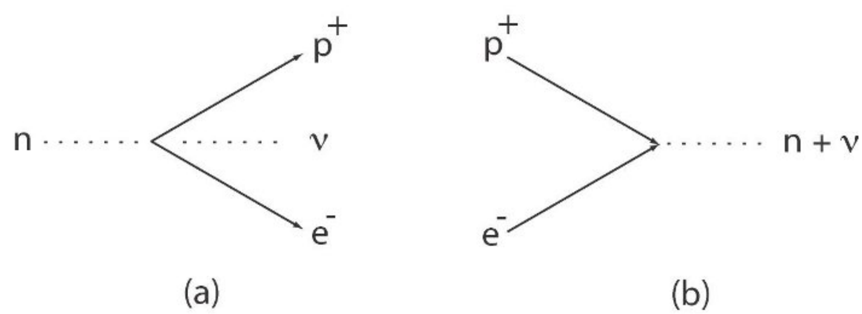

Figure 1. Two simple nuclear reactions. The dotted lines symbolize the conjectured trajectories of unobservable particles.

Figure 1a symbolizes the disintegration of a neutron (dotted line) into a proton, an electron, and a neutrino. Figure 1b depicts the nearly inverse reaction: the synthesis of a neutron and a neutrino out of a proton and an electron. The dotted lines stand for invisible (because electrically neutral) particles. To figure out these reactions physicists use not only knowledge about the incident beams, but also the law of momentum conservation: the vector sum of the momenta of the "visible" particles must equal the momentum of the invisible thing or things. In both cases this law suggests that the missing component, though invisible, is actually there. That is, the presence of the neutral particles is betrayed by its not leaving a trace–just like the silence of the hound of the Baskervilles in Conan Doyle's story suggested to Holmes that the dog was familiar with the criminal. Once more, and contrary to the positivist dogma, data do not cover all the facts out there, whereas good theory does.

A crucial difference between the indicators used in physics, chemistry, and biology, on the one hand, and those used in daily life and in the social sciences on the other hand is this. Whereas the former are backed by reliable theories, the latter are either empirical or backed by dubious theories–as when national development was identified with growth in GDP.

IV. Theory-based Indicators

A theoretically justified indicator is an observable property v that is functionally related to an unobservable u by a precise formula of the form $u = f(v)$. (Roughly, the inverse of f maps states of the mensurandum into states of the mensurans. In other words, f is the code that allows one to read noumena from phenomena.) A formula of this type is not empirical, but part of the theory of the measuring instrument in question. In the case of the galvanometer, electrodynamics shows that the intensity i of an electric current is proportional to the tangent of the angle θ of the deviation of the needle. This shows that there is theory behind pointer reading–a fact emphasized by Pierre Duhem (1914) a century ago.

Presumably, the Sumerian craftsmen and traders who invented or used the earliest measuring devices did not lose much sleep over scientific indicators: they proceeded empirically. On the other hand the nineteenth century scientists and engineers who designed the earliest precision instruments must have invested much ingenuity in mapping theoretical unobservables into laboratory observables. Some of that ingenuity went into writing the laboratory manuals familiar to the physics students of my generation, such as Kohlrausch's (1873) tough and dry textbook on physical measurements.

The fact that the design of good experiments is oriented by theories explains the utter failure of the pedagogical constructivists–who claim that children will find the laws of nature by themselves–to inspire and educate future scientists. Besides, theories are invented, not discovered; and all scientific theories contain concepts, such as those of atom, metabolism, social cohesion, and price elasticity, that denote imperceptible items.

The same facts explain the impotence of amateurs in the laboratory, where all they can do is to stand in the way of researchers and break pieces of equipment. This is why the sociologists and anthropologists who, like Latour and Woolgar (1979), spent some time in a laboratory, never understood what their subjects were up to. Consequently they gave an utterly distorted description of scientific research, namely as "social construction" of reality and struggle for power.

Some sociologists in the late twentieth century realized that the construction and empirical test of quantitative hypotheses require indicators. They started what became known as the social indicators movement, which in 1974 got a journal of its own, *Social Indicators Research*. The same year UNESCO held a conference on development indicators, where a multidimensional indicator of human development was first suggested (Bunge 1974). This was a precursor of the three-dimensional (biological, economic, and educational) indicator of human development adopted by the UN in 1989 despite the resistance of the economists who claimed that the GDP, a measure of economic activity, was sufficient.

V. The Place of Indicators in Theory Testing

We are now ready to look at the place of indicators in the experimental testing of scientific theories. What can be empirically tested are not general theories, such as classical or quantum mechanics, but theoretical models, or applications of such theories, to special cases, such as a theory of a planet or of a helium atom. The reason should be obvious: there is no general body or general atom. Any such model M is either built from scratch ("free model") or gotten by enriching the general theory G with a set S of subsidiary assumptions representing some salient properties of the thing in question. That is, $G \cup S \vdash M$.

But, contrary to the standard view on testing, not even such specialization brings the theory down to the empirical level. To take a theory into the laboratory we must combine the theoretical model M with a set I of pertinent indicators. For example, if the theoretical model to be tested involves the intensity i of an electric current, we replace i with $k{\cdot}tan\,\theta$, where k is a constant that characterizes the instrument, and the angle θ is read on the dial.

Likewise, the mass spectrograph allows atomic physicists to visualize the differences between the masses of isotopes; chromatography revolutionized organic chemistry by allowing chemists to compare molecular masses through the straightforward expedient of comparing the tracks left on blotting paper by solutions of different compounds traveling under the action of an electric field; and fMRI (functional magnetic resonance imaging) has greatly helped cognitive neuroscience mature by showing on a screen the metabolic activity of a brain region, an indicator of neural activity, much as GDP indicates at a glance the intensity of economic activity of a nation.

In short, what is directly confronted with empirical data is not a general theory G, nor even a theoretical model M (or special theory) based on G, but its operationalization O, which is the translation of M into the relevant indicators I (Bunge 1967). Thus, the process of theory testing involves the construction of a deductive tree of the form:

Remove indicators, and no empirical tests become possible. And yet, ironically, none of the philosophical champions of empirical testing has ever mentioned indicators–which may be taken as an indicator of the remoteness of their opinions from scientific research.

However, in this regard the founders of quantum mechanics sinned too. In fact, one of their main dogmas was that, as decreed by what used to be called "the bible of quantum mechanics," "every eigenvalue [of an

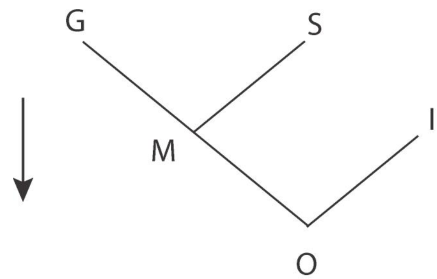

Figure 2. The deductive tree involved in the empirical test of any high-level theory. Simplified from Bunge (1967).

operator representing a dynamical variable] is the possible result of the measurement of the dynamical variable for some state of the system" (Dirac 1958, 36)–regardless of the measurement procedure.

Those eminent physicists should have known that such microphysical measurements are extremely indirect, as they involve indicators and pieces of apparatus, such as amplifiers, that only a (classical or semi-classical) theory can explain. Furthermore, they should have known that what we read on most pre-digital precision instruments are angles–and yet it so happens that angles are not dynamical variables represented by operators with eigenvalues and eigenfunctions. Shorter: Angles, genuine observables, are not "observables" in the Pickwickian sense employed in the quantum orthodoxy.

To his credit, Niels Bohr (1958), the father of the (Copenhagen) interpretation in question, rightly emphasized the dependence of the tests of quantum mechanics upon classical physics. But he did not realize that any realistic descriptions of measurements, such as his own, are inconsistent with that interpretation of the quantum theory.

In fact, according to quantum orthodoxy, this theory describes observations rather than independently existing physical objects. Thus, Heisenberg (1969, 171) held that atoms "are parts of observation situations." But this claim is shown to be false by remembering that stars, where observations are impossible, are made of atoms. Besides, an analysis of the variables occurring in the basic formulas of the theory shows that none of them involves measuring instruments or even indicators–both of which belong in the laboratory (Bunge 1967b). If theories did contain such items, it would be impossible to confront them with empirical findings: judges are not expected to try themselves.

Unsurprisingly, the general quantum theory of measurement, founded by the mathematician John von Neumann, does not include any indicators. This theory is supposed to hold for measurements of all kinds, invasive like those involving colliders, and non-invasive like those using spectrographs.

It thus assumes tacitly the existence of a universal meter. But of course there is no such thing: All measuring instruments are specific, and their design involves special theories. For example, interferometers work with light, not with atomic beams; and their design and operation requires optics, not thermodynamics. No wonder then that, after eight decades, the general quantum theory of measurement has never been put to the test, and has never helped design any real experiment. It is just a prosperous academic industry employing scholars who have never set foot in a laboratory.

VI. Conclusions

The preceding suggests a few philosophical morals. First: Measuring instruments, together with the indicators they embody, bridge imperceptible noumena (things-in-themselves) to the corresponding phenomena (things-for-us). Second: The mere existence of such bridges falsifies phenomenalism, the doctrine according to which noumena either do not exist or, if they do, are unknowable. Third: The fact that, to be tested, a high-level hypothesis has got to be conjoined with indicator hypotheses, falsifies the naïve logic of empirical testing held by positivists and Popperians alike.

In sum, it has been known since the 1600s that experimental interventions suggest or test representations of reality. But all experimental designs are based on theories–a case of virtuous circle. No intervention without representation.

Mario Bunge
FRSC Frothingham Professor of Logic and Metaphysics
McGill University Department of Philosophy
855 Sherbrooke St. West
Montreal, QC
Canada H3A 2T7
mariobunge@mac.com

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